

STATE OF THE ART OF RESERVOIR SEDIMENTATION MANAGEMENT IN SPAIN

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ABSTRACT

Part of the total reservoir storage capacity in Spain (56 km³) is lost due to sedimentation processes taking place. Surveys carried out in 121 reservoirs indicate that 6% of them have undergone a capacity reduction of over 50%. However, most of them (81%) are characterised by a reservoir capacity loss below 20%.

The most frequent methods used to control reservoir sedimentation in Spain fall into one of the following groups: reduction of sediment yield through basin management and removal of the sediment deposits that have built up.

Reduction of sediment yields includes soil and water conservation programmes, upstream sediment trapping debris dams, and bypassing of sediment. In Spain, soil and water conservation programmes, mainly those involving afforestation practices and engineering measures, have been carried out since 1877.

Flushing and excavation practices are being used to remove part of the sediment build-up from some reservoirs. With regard to this, the empty flushing of the Joaquín Costa (Barasona) reservoir is highlighted, since it was the first controlled flushing undertaken in our country. Prior to the flushing, all sectors concerned in the Barasona Reservoir activities were consulted. Sediment evolution and environmental factors, such as water quality, fisheries, riparian vegetation, fauna, etc., were studied before, during and after the flushing. In general terms, the experience was found to be so satisfactory that it is being taken into consideration when planning other reservoir flushings.

In Spain, all reservoirs are provided with bottom outlet(s), so that they can be subjected to flushing. This has been a deciding factor when considering regular flushing as one of the most suitable method for sedimentation control. Once the specific characteristics of each individual reservoir have been taken into consideration, regulations and standards are drawn up and applied to ensure minimum impact and the maximum accuracy of flushing operations. It is expected that this silting mitigation measure could soon be regularly applied to all reservoirs.

KEY WORDS: Sediment/control/reservoir/capacity losses/Spain.

1. RESERVOIRS IN SPAIN

Spain, together with Portugal, form the Iberian Peninsula, which is the most westerly land mass in Europe. Spain covers a surface area of 505,956 km² and most of the country lies on the mainland. The Balearic Islands, in the Mediterranean Sea, and the Canaries Isles, in the Atlantic Ocean, constitute the rest of the territory.

There are ten major river basins on the Iberian Peninsula, managed by the following River Basin Authorities: 1 North, 2 Douro, 3 Tagus, 4 Guadiana, 5 Guadalquivir, 6 South, 7 Segura, 8 Júcar, 9 Ebro and the 10 Inland Basins of Catalonia (Fig. 1).

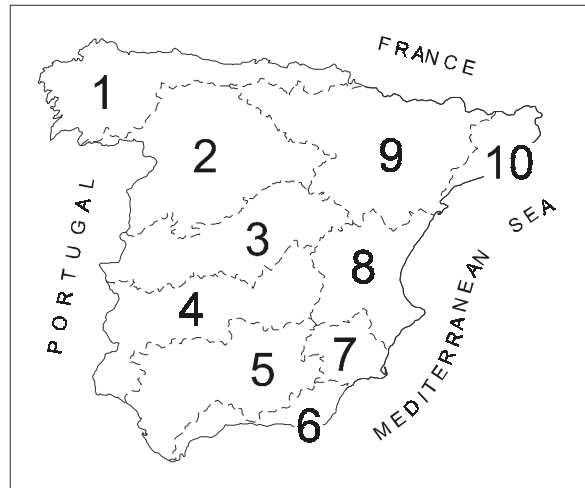


Figure 1: River Basin System

According to Mahmood (1987) a total of 5,000 km³ of water is stored in reservoirs throughout the world. This value amounts to 13% of the annual yield. The annual sedimentation rate is approximately 50 km³, i.e., about 1% of the total volume stored. At that time, the total volume stored in reservoirs in Spain was 54.6 km³, slightly over 1% of the world total. This value accounts for more than 50% of the annual yield in Spain.

Spain currently has 1,133 dams in operation for 1,040 reservoirs, and the total volume of water impounded is slightly more than 56 km³. 98% of the total storage capacity is concentrated in 300 large reservoirs whose capacity is greater than 10 hm³ (Fig. 2).

2. SEDIMENTATION IN RESERVOIRS. STUDIES UNDERTAKEN BY THE CEDEX

In 1967 the Centro de Estudios y Experimentación de Obras Públicas (CEDEX) was commissioned by the Dirección General de Obras Hidráulicas (Hydraulic Works Directorate) to carry out a bathymetric survey of a series of reservoirs located in the upper reaches of a series of river basins where the erosion processes could have an adverse effect upon the working life of the reservoirs themselves. After the surveys had been completed and the findings analysed, it was found that not only the slope, but also other factors such as anthropic activities, could also have a major effect on the amount of solids flowing into reservoirs. In view of this phenomenon and other considerations, it was decided to apply the study to other reservoirs proposed by the different River Basin Authorities, because these bodies are in the best position to know what problems are faced in the basins under their control.

Up to the present time, just over 120 of the 1,040 reservoirs in operation have been surveyed, i.e. about 12% of the total (Fig. 2). "A priori" it would appear to be inadvisable to draw conclusions in view of the small number of individual reservoirs analysed. However, if one thinks in terms of the total surface area covered by the reservoirs studied (220,200 km²) and compares this with the total surface area throughout the country, it can be seen that approximately 45% has been subjected to analysis, and this considerably increases the reliability of the conclusions that have been reached.

Methodology for measuring silting in reservoirs

Updating the capacity curve

Before one can measure the degree of silting in a reservoir, one must first know the latter's original storage capacity. The other essential information that one must have if one is to find out the volume of

sediments deposited, is to know the reservoir capacity on a specific date. The difference between the two volumes indicates the amount of sediment that has built up in the reservoir.

Reservoirs that are subject to a normal operating system are only completely empty or completely full for short periods of time. Therefore, the capacity curve for a reservoir is normally obtained using two supplementary procedures, photogrammetry and bathymetry. In the former case, the aerial mapping of the reservoir basin takes place and then the photogrammetric information is analysed. Potting is then carried out to obtain the topography of the land lying above the water level on the day of the flight. The part of the reservoir basin that is submerged beneath the water surface on the flight date can be obtained from the information provided by the bathymetric survey. A combination of the two surfaces is then used to obtain the reservoir layout plan on the basis of the contours. Once the surface lying within each contour has been calculated, a suitable calculation algorithm is used to obtain the elevations - surfaces - volumes deposited table. The value thus yielded is the Maximum Normal Reservoir Level elevation under consideration, which defines the reservoir capacity (Avendaño et al., 1997).

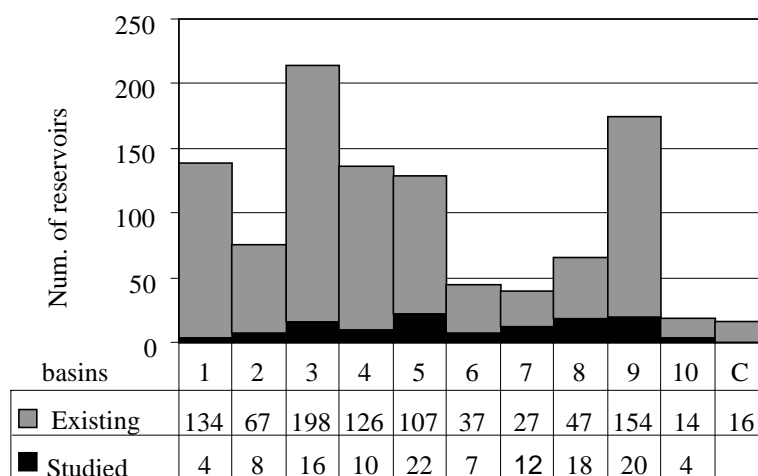


Figure 2: Reservoir distribution in River Basins. C = reservoirs under construction

Reservoir sedimentology studies

The main aim of sedimentological studies is to calculate the sediment density, which enables the engineer to convert the volumes that have built up, into units of weight, because compaction causes the volumes to change in the course of time. The methodology proposed by ICOLD (1989) is used to make these calculations.

Reservoir capacity loss

It must be pointed out that volumes greater than the original ones were obtained for some reservoirs that had been in operation for several years. There could be two explanations for this phenomenon: firstly, errors that might have been made in the data concerning the initial reservoir volumes (photogrammetry in Spain was first developed in the 1950's) and, secondly, the margin of error permitted for the methodology used in the photogrammetry and bathymetry work. This state of affairs could happen in cases where the real capacity loss is negligible (< 5%).

From 121 reservoirs surveyed 81% showed a capacity loss of less than 20% of their total volume and 94% of the reservoirs have undergone a capacity loss due to silting of less than 50%, throughout the period for which they have been in operation.

16 of the reservoirs have shown an annual volume loss of at least 1%, and silting problems begin to occur when the annual loss is greater than this percentage. Two of these reservoirs have been excluded, because of doubts about their initial volume and waterproofing treatment, which means that only 14 of the 121 reservoirs (11.6%) could be having sedimentation problems.

Table 1: Capacity loss (%) for the different River Basins

3. RESERVOIR SEDIMENTATION MANAGEMENT

Watershed management

Different solutions have been taken for other reservoirs. In the case of the Cubillas Reservoir (Guadalquivir River Basin), it is intended to make use of the existence of a diversion dam for the bypassing tunnel and convert it into a silt dam. It is planned to equip the diversion dam with 2.5 m high gates, thereby creating a stilling pond upstream with a retention capacity of 75.000 m³ (Masa, 1996). Most of the suspended sediments contained in normal flows will be deposited in that basin. The sediment-free water will flow over the sluice gates into the reservoir. The mud that builds up during this process will flow out through the bypassing tunnel during periods of flooding.

The River Cubillas Reservoir, with a storage capacity of 21 hm³, was provided with a bypassing tunnel in 1951. This tunnel was constructed so that the muddy waters could flow out when this river was flooding, so that the reservoir would not silt up quickly. This tunnel leads off from the aforementioned diversion dam and flows into a tributary of the River Cubillas, the confluence of these two rivers lying downstream from the dam. The tunnel has an outflow capacity of 150 m³/s.

Removing the sediments that build up

Dredging and mechanical digging

The partial or complete removal of the sediments that have built up in some Spanish reservoirs has been carried out by excavation. There are a variety of reasons for resorting to this methodology, for example, the Foix, Linsoles, Gállego and Sarra Reservoirs were partially *dredged* in order to release the bottom outlets (Serrano, 1997), and 8.500 m³; 15.000 m³, 5.000 m³ and 5.000 m³, respectively were removed from them. The Barasona Reservoir (Avendaño et al., 1997a) was also dredged for the same reason, but the characteristics of the sediment in the vicinity of the dam meant that the yield was very low (5%), so other techniques were used.

Excavations using mechanical techniques other than dredging have also been carried out. These excavations were both partial, e.g., for the Puentes Reservoir (Cobo et al., 1997) or complete, e.g., in the Proserpina Reservoir (where a total volume of 914.000 m³ of sediments were removed).

The excavated sediment was eventually disposed of in a variety of different ways, depending on the zone. In the case of the Proserpina Reservoir it was taken to tips, after it had been suitably treated (Alcaraz and Vázquez, 1994). The 100,000 m³ of mud removed from the Valbona Reservoir (River Júcar Water Authority) are to be used to restore and reforest a disused quarry (Solanes and García, 1996).

Flushing. Completely emptying the Joaquín Costa Reservoir (Barasona)

The Joaquín Costa or Barasona Reservoir, River Ebro Water Authority, is earmarked for a variety of uses; irrigation (600 km²), water supply for the population and industry (50,000 inhabitants) and generating electricity. The dam came into operation in 1926 and was heightened in 1976. The crest of the dam is 60 m. above the foundations and the initial capacity of the reservoir was 92 hm³. Since it came into service 16 hm³ of sediment has built up, and these deposits have reached a height of 24 m above the original water-course. The bottom outflows were completely clogged up and the only available outlet, lying 21 m. above the former riverbed, was partially blocked.

In August 1993, when the water level in the reservoir was very low there was a heavy storm, and the outlet became completely blocked. Irrigation was temporarily suspended. In the face of these events, a decision was taken to completely flush and dredge the reservoir, to extract all the mud deposited in the vicinity of the dam and the outlets and to restore the bottom outlets to their original state. It was considered that this would guarantee the periodical outflow of all the mud that builds up in the outflow, and prevent the likelihood of any further blockages.

The complete flushing of a reservoir brings about two groups of effects or environmental disturbance, as a result of the total loss of the water mass and allowing the mud to flow into the riverbed.

A decision was taken to set up four committees whose function would be to give advice to the Confederación Hidrográfica del Ebro (River Ebro Water Authority) about the decisions to make in order to carry out the flushing correctly and to prevent the negative effects or to reduce them to a minimum. The four committees established and their respective functions were as follows:

- Scientific Committee. Basically comprising university lecturers and professors and research bodies. They performed the scientific studies, before during and after the flushing, which made it possible to obtain a greater in-depth working knowledge of the environmental impact of complete and prolonged flushing activities.
- Experts Committee. Consisting of specialists from the different administrative bodies, anglers associations and ecologist groups in the zone. This committee advises the Water Authority in matters concerning the provisional resumption of the supply services affected, rescuing and relocating fish, monitoring and controlling the flushing, and taking any preventive and corrective measures to reduce negative environmental impact to a minimum.
- Users organisation. Composed of irrigation subscribers, personnel from hydroelectric and industrial companies and local councils and those who make direct use of the reservoir or river banks affected. This committee decided upon the most suitable schedules for the different flushing activities, the restoration works for the bottom outlets, compatibility with the different uses, the provisional replacement works for the various population supply services affected and the temporary river operations.
- Institutional Committee. Made up of the political authorities in the different provinces affected. They were furnished with information about the activities to be carried out or decisions taken.

The following studies were undertaken to find out what environmental impact took place as a result of the flushing: (a) river fauna y vegetation, (b) lymnology of the reservoir and affected stretches of the river, (c) fish population in the reservoir and river, (d) state of the soils in the reservoir drainage basin, (e) the dynamics of the sedimentation processes in the reservoir and the river basin, (f) bathymetric and sedimentological surveys in the reservoir, and (g) control of suspended solids. The data obtained from the suspended solids control is shown below. The results from the remaining studies are summarised in a special volume of the specialist journal *Limnética* (1998).

Three complete and continual flushings were carried out (each lasting from 2 to 3 months) 3 years' running. The suspended solids that flowed out in the three flushings all behaved in a similar way. At the first flushing stages the water flowed out of the reservoir with a low suspended-solid concentration, less than 1 g/l. Then, the reservoir began to operate as a river system, which was when the major concentration peak was reached, values of 500 g/l. being recorded. After that point, the concentration of solids dropped rapidly, and stabilised at 70-80 g/l. The concentration then fell gradually but consistently, with peak values of certain relevance, albeit lowering in time (when there was rainfall in the basin).

When a comparison is made between the storage capacity data obtained by the CEDEX in 1993 (before the first flushing) 75.940 hm³, and the data for 1998 (after the flushings) 84.798 hm³, it can be deduced that the total volume of sediment removed from the reservoir amounted to almost 9 hm³.

Although the first flushing had a major environmental impact, the first few kilometres of the river were covered by a mass of mud up to 8 metres deep, after about 20 days the river opened up a channel and

washed most of the sediment away. After 6 months, not only had the habitat downstream from the dam recovered, but it was actually in a better state than before.

The conclusions that can be drawn from the Barasona Reservoir experience, which serves as an example for others that are being planned, in view of the fact that it was the first of its kind to be carried out in Spain, are as follows:

- Those who are responsible for operating a dam sometimes have to completely flush the reservoir, which has a negative environmental impact, but this is inevitable if the reservoir and the dam are to remain operational and safe.
- One challenge currently facing engineers is to give top priority to respecting the environment when planning, constructing, conserving and operating the works that society commissions them to undertake. In return, society accepts the greater initial cost that this type of activity requires.
- Engineers must be prepared to work in multi-disciplinary teams with other experts, scientists, users, ecologists, etc., conversing, listening, understanding and accepting other points of view.
- An effort must be made to plan and construct in a completely transparent way with the participation of society, and to explain to society the reason for the works, in order to ensure that society does not protest.
- It would be advisable to set sufficiently detailed standards, which define the procedures and the ways of flushing reservoirs.

Partial Flushing

Partial flushing through the bottom outlets, for which legal provisions exist for all Spanish reservoirs, are subject to regulations in the respective River Basins, through the Operating Standards concerned, which are drawn up on an individual basis for each reservoir.

"*The Technical Regulations affecting dams and reservoirs safety*" require the bottom outlets to be fully operational and free of sediment. With a view to this, it is general practise to completely or partially open the gates for a few hours every so often (on a monthly or quarterly basis, etc.)

Activities downstream from the reservoir. Ecological flows

An ecological flow is one that can meet the requirements of a river so that it can function as an ecosystem. There are no specific regulations to determine exactly what this flow has to be in each particular case. However, every Autonomous Region - as part of its jurisdiction in matters concerning the environment - has begun to implement provisions with respect to the minimum flows needed to fulfil the ecological requirements for each specific case.

Another aim of providing ecological flows is to provide the river with a sediment yield downstream from the dam.

CONCLUSIONS

From Spanish reservoirs analysed 81% have undergone a total capacity loss of less than 20%, and only 7 out of 121 have lost more than 50% of their original capacity. It can thus be concluded that there are no major capacity loss problems. Approximately 11.6% of Spanish reservoirs are experiencing silting

problems. The presence of this sediments not only limits the benefits provided by the reservoirs concerned, but also brings about a lack of sediment downstream from the dam, thereby preventing the riverbeds from operating correctly (e.g., Sanz et al., 1999). Therefore, it is necessary to take measures in Spain to overcome the problems arising from the build-up of sediment in the reservoirs. Up to the present, the measures taken have revolved around basin management, basically reforestation, together with the construction of diversion dams and debris dams.

At present, and making use of the bottom outlets that all Spanish dams are equipped with, the reservoirs are being flushed periodically, because this is the best way to ensure that the outflow structures operate properly. If there is a considerable build-up of sediment or the outlet gates are not working correctly, the reservoirs can be completely flushed. The Barasona Reservoir is an example of such activities take place successfully.

Whatever technique is chosen to manage sediments, it is advisable to resort to multi-disciplinary teams to study and supervise the actions that are taken.

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